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Durability Testing of a Toyota LCS-M (Lean Combustion System-Methanol) Carina

(U.S.) Environmental Protection Agency, Ann Arbor, MI

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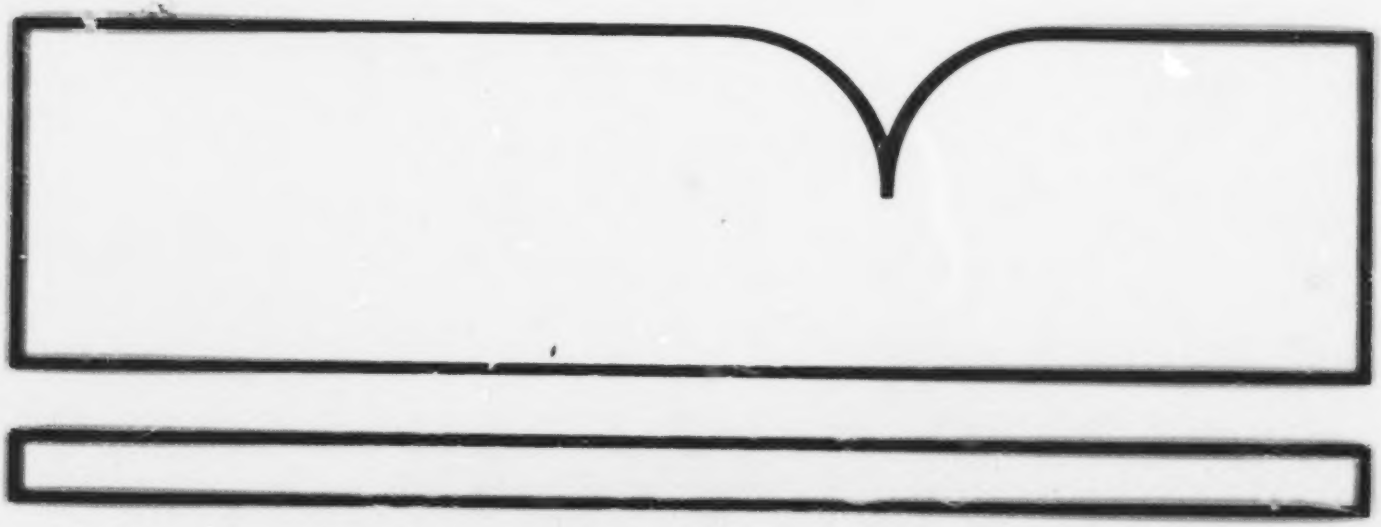

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Technical Report

Durability Testing Of A Toyota LCS-M Carina

by

Gregory K. Piotrowski

June 1989

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16. ABSTRACT

This report describes the exhaust emissions, fuel economy and oil sample analysis from a Toyota LCS-M Carina motor vheicle fueled with M100 fuel. The vehicle accumulated 6,000 miles driven over the AMA durability driving schedule in order to determine if exhaust emissions levels increase during the first 5,000-15,000 miles of driving with a light-duty methanol fueled vehicle.

The program description, test vehicle description, test facilities and the test vehicle specifications are included.

17. KEY WORDS AND DOCUMENT ANALYSIS

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I. Summary

Some industry representatives have stated in private conversations with EPA personnel that their research suggested that late-model, catalyst-equipped light-duty methanol vehicles experience a significant rise in pollutant emission levels during the first 5,000-15,000 miles of driving. It was therefore decided to accumulate approximately 6,000 additional miles on a methanol-fueled vehicle under carefully controlled conditions to note any "step-change" behavior in emission levels.

Accumulation of 6,000 miles over the Durability Driving Schedule described in Appendix IV of Part 86, 40 CFR Chapter 1, with an M100-fueled Toyota LCS-M Carina vehicle has been completed. Approximately 4,450 miles of driving on a chassis dynamometer with this vehicle had occurred prior to the start of this mileage accumulation. The driving was performed under contract by Automotive Testing Laboratories, Inc. (ATL). The vehicle was equipped with the same manifold close-coupled platinum-rhodium catalytic converter before and during this testing. Toyota provided this catalyst when the car was delivered to EPA during 1986.

Emissions of hydrocarbons (HC), organic material hydrocarbon equivalents (OMHCE), methanol (CH_3OH), carbon monoxide (CO) and formaldehyde (HCHO) over the FTP cycle did not substantially change during this durability testing. Emission levels of these pollutants at the completion of this project were similar to emission levels during July 1988, several months prior to the start of this project.

NOx emissions increased slightly over the first 3,000 miles of this project, from 0.89 to 1.01 grams per mile. NOx was measured at a higher level of 1.42 grams per mile at the end of the project. ATL technicians noted a slight misfire at low-speed cruise conditions during the final 500 miles of mileage accumulation; this condition was not apparent during the emissions testing of the vehicle after it was returned to the EPA laboratory, however. NOx emissions have been measured at 1.04 grams per mile during FTP testing conducted with this vehicle since the completion of the work described in this report, however.

City and highway fuel economies were essentially unchanged during this project. The gasoline equivalent composite MPG measured during March 1989, was the same as that measured during December 1986.

The oil sample taken after the first 1,500 miles of project driving showed metal contaminant wear levels twice as high as samples taken during the remainder of the mileage accumulation. The first sample was from a 30-weight oil; approximately 500 chassis dynamometer miles had been accumulated with this oil in the engine before durability testing commenced, for a total of almost 2,000 total miles driven prior to sampling. The oil was then changed to a multi-viscosity formulation; this oil was then sampled and changed in approximately 1,500-mile increments three times.

II. Background

The subject of variability in emission levels over time with methanol engine operation was discussed during several recent meetings between EPA and automotive industry representatives. Some industry representatives stated that their research suggested that late model, catalyst-equipped, light-duty methanol vehicles experienced a significant rise in overall pollutant emission levels during the first 5,000-15,000 miles of driving. This increase in emissions apparently occurred in a very noticeable manner; the nature of the increase was a step-change of considerable magnitude over a short period of time. These industry representatives did not specify the magnitude of this step-change, however. Pollutant emissions were described to be relatively constant before and after this step-change.

This step-change increase in emission levels had not been noticed on methanol vehicles tested previously at the EPA laboratory. Engine-out emission levels were plotted against odometer mileage during October 1985, for the 1981 M100-fueled Volkswagen Rabbit used as a test vehicle for the ECTD methanol catalyst test program.[1] The odometer miles over which these emission levels were tracked was the interval 3,000-15,000 (dynamometer) miles driven. The cycle driven was the FTP cycle.

CO levels declined from approximately 7.5 grams per mile during the interval 3,100-8,500 odometer miles to 5.4 grams per mile at 15,000 miles. Engine-out CO then rose steadily, however, back to 7.5 grams per mile over the FTP currently (19,000 miles driven). NOx levels were approximately 2.0 grams per mile at 3,000-7,000 miles; this level dropped off steadily after 7,000 miles however, and has stabilized at approximately 1.7 grams per mile. HC rose slightly from 1.0 grams per mile at 3,000 miles to 1.14 grams per mile at 9,000 miles. HC levels have fallen steadily since then to approximately 0.90 grams per mile currently. HCHO emissions varied from 180 to 560 milligrams per mile during this period of vehicle usage; HCHO level did not consistently increase or decrease during that time period, however. The lack of a trend and the relatively large variations in HCHO emissions over time from this vehicle have been previously noted.[2]

This information was concerned with engine-out emission levels only; a catalyst was not present on the vehicle. Deterioration of a catalyst through poisoning, overtemping, etc. could cause a significant increase in emission levels from a catalyst-equipped vehicle.

Another ECTD-sponsored study looked at emission level changes with catalyst aging.[3] It was thought that aging a catalyst on a methanol-fueled vehicle different than the test vehicle used for emissions testing would provide useful information on the emission level increase caused by aging of the catalyst only.

New samples of two noble metal catalyst configurations, each at a loading of 20 grams per cubic foot, were emission tested on a methanol-fueled Toyota Cressida. These catalysts were then aged approximately 12,000 miles each on a fleet of methanol-fueled 1983 Ford Escort vehicles. The California Energy Commission (CEC) was responsible for maintenance of the Escort fleets and accumulation of the driving miles on the subject catalysts.

The results from emissions testing over the FTP cycle after aging were mixed. When tested in a three-way mode, catalysts with a formula and loading of 3Pt:2Pd(20) showed virtually no change in emission levels after aging; HC efficiency actually increased approximately 2 percent with aging. Pd(20) catalysts uniformly decreased in efficiency with aging; efficiency decreases ranged from 6 percent for HC to 40 percent for NOx emissions. When tested in an oxidation catalyst mode, the 3Pt:2Pd(20) catalysts substantially decreased in HC and CO efficiency after aging. The aged catalysts had increases in NOx and aldehyde efficiency of 15 and 50 percent respectively, from non-aged catalyst levels, however. The aged Pd(20) catalysts exhibited increases in HC, NOx, and aldehyde efficiency over fresh catalyst levels in the oxidation mode; only CO showed a decrease in catalyst efficiency with aging.

Several factors may have combined to reduce the usefulness of this study of catalyst durability on a methanol-fueled vehicle. First, the catalysts reported here were loaded with noble metal at 20 grams per cubic foot; our interest at that time was in a lower cost approach to methanol vehicle catalysts. Subsequent ECTD testing [4] has suggested that noble metal catalyst loadings two or three times as large as those in reference 3 may be necessary in order to reduce emissions to lower levels. Hence, those catalysts tested may not be representative of catalyst configurations which may be placed on future methanol-fueled fleet vehicles. Second, mileage accumulation on the Escorts was very uneven. Some

selected cars were signed out almost continuously, while some were utilized only on those occasions when a great number of cars were needed. The level of maintenance on those cars also dropped off appreciably during the test program. The cars were operated by a number of drivers, on a number of unknown routes, under a number of different driving conditions, often with maintenance different from that recommended by the manufacturer. Therefore, the mileage accumulation was conducted under much less than ideal conditions. Finally, it was necessary to perform non-routine, unscheduled maintenance on the Toyota Cressida emissions test vehicle on numerous occasions during the test program. Several of the services included replacing the engine fuel injectors. The availability of a more reliable emissions testing vehicle would have assisted this program considerably.

It was therefore decided to accumulate approximately 6,000 miles on a methanol-fueled vehicle under more carefully controlled conditions to note any "step-change" behavior in emission levels. The vehicle chosen for this work was a Toyota Carina equipped with the Toyota Lean Combustion System Methanol (T-LCS-M).

III. Program Design

This project involved the accumulation of 6,000 miles on an M100-fueled test vehicle under carefully controlled conditions in order to note any "step-change" behavior in emission levels over this time period. The test vehicle was a methanol-fueled Toyota LCS-M Carina equipped with a manifold close-coupled catalytic converter.

The driving was performed under contract by ATL at the Bendix test track located in South Bend, Indiana. The driving was conducted during the time period of November 1988 through March 1989. The 6,000 miles were accumulated on the vehicle in two 3,000-mile increments. The vehicle was emission tested by EPA prior to its initial consignment to ATL; upon completion of the first 3,000-mile increment, the vehicle was returned to the EPA motor vehicle laboratory and emission tested. The car was then consigned again to ATL for the second 3,000-mile driving increment. Upon completion of this work, the vehicle was returned to EPA for emission testing.

The driving cycle used for this work was the Durability Driving Schedule described in Appendix IV, Part 86, 40 CFR, Chapter 1. A description of this driving cycle is given in Appendix A. All of the driving was conducted on the test track, rather than on a chassis dynamometer. The engine oil was changed at 1,500-mile increments and the waste oil was saved for metals analysis. Results from testing are presented in the Discussion section.

IV. Test Vehicle Description

The Toyota Lean Combustion System (T-LCS) was described in a paper appearing in the Japanese Society of Automotive Engineering Review (JSAE) for July, 1984.[5] This system made use of three particular technologies [6] to achieve improvements in fuel economy as well as to comply with NOx emission levels under the Japanese 10-mode cycle:

1. A lean mixture sensor [7] was used in place of an oxygen sensor to control air/fuel ratio in the lean mixture range;

2. A swirl control valve before the intake valve was adopted to improve combustion by limiting torque fluctuation at increased air/fuel ratios; [8] and

3. Sequential fuel injection with optimized injection timing was used to complement the operation of the swirl control valve.

The Toyota Lean Combustion System Methanol (T-LCS-M) is similar to the T-LCS, but has been modified to maximize fuel economy and driving performance while minimizing pollutant emissions through the use of methanol fuel. SAE Paper 860247 [9] described the development of the T-LCS-M system.

EPA became interested in this system because of its use of fuel methanol and Toyota provided EPA a T-LCS-M system in a Carina chassis. The Toyota Carina is a right-hand-drive vehicle sold in Japan, but currently not exported to the United States. The power plant is a 1587 cc displacement 4-cylinder, single-overhead camshaft engine. The engine was modified for operation on methanol in a lean-burn mode, incorporating the lean mixture sensor, swirl control valve and timed sequential fuel injection found on the Toyota lean combustion system. Modifications to the fuel system included the substitution of parts resistant to methanol corrosion for stock parts.

Initial testing of this vehicle at the EPA Motor Vehicle Emissions Laboratory involved the use of both M85 and M100 methanol fuels. This "Phase I" testing involved the determination and comparison of fuel economy and pollutant emission profiles of the vehicle when operated on each of these fuels. A summary of this testing was published in SAE Paper 871090.[10] Testing subsequent to Phase I involved a number of separate issues concerned with various aspects of the T-LCS-M system. This testing was conducted using M100 neat methanol exclusively, and was referred to as "Phase II" testing.[11]

Detailed test vehicle specifications are provided in Appendix B.

V. Test Facilities and Analytical Methods

Emissions testing at EPA was conducted on a Clayton Model ECE-50 double-roll chassis dynamometer, using a direct-drive variable inertia flywheel unit and road load power control unit. The Philco Ford constant volume sampler has a nominal capacity of 350 CFM. Exhaust HC emissions were measured with a Beckman Model 400 flame ionization detector (FID). HC test results in the text are presented without accounting for FID response to methanol or the difference in HC composition because of the use of methanol fuel. CO was measured using a Bendix Model 8501-5CA infrared CO analyzer. NOx emissions were determined by a Beckman Model 951A chemiluminescent NOx analyzer.

Exhaust formaldehyde was measured using a dinitrophenyl-hydrazine (DNPH) technique.[12,13] Exhaust carbonyls including formaldehyde are reacted with DNPH solution forming hydrazine derivatives; these derivatives are separated from the DNPH solution by means of high performance liquid chromatography (HPLC), and quantization is accomplished by spectrophotometric analysis of the LC effluent stream.

The procedure developed for methanol sampling and presently in-use employs water-filled impingers through which are pumped a sample of the dilute exhaust or evaporative emissions. The methanol in the sample gas dissolves in water. After the sampling period is complete, the solution in the impingers is analyzed using gas chromatograph (GC) analysis.[14]

VI. Discussion

A. Emission Test Results

Table 1 and Figures 1 and 2 present FTP emissions results from the test vehicle at several dates and odometer readings before the durability testing for comparison. The testing during October 1988 was conducted prior to the initial consignment of the vehicle to ATL. The testing during February 1989 was conducted at the 3,000-mile completion point, while March 1989 denotes testing after completion of the 6,000 durability miles.

Emissions measured as HC over the FTP did not change markedly from levels measured during December 1986. During the 6,000-mile durability accumulation HC levels remained essentially constant.

These HC exhaust emissions from an M100-fueled vehicle may be occurring from the engine oil which is incompletely oxidized in the combustion chambers and catalytic converter. Oil may enter the combustion chambers as cylinder wall lubrication, particularly on the compression and exhaust strokes, and from the crankcase ventilation system.[15,16]

Table 1

Toyota LCS-M Carina
Emission Test Results, FTP Test Cycle

Date	Approximate Odometer (miles)	HC (g/mi)	HC* (g/mi)	OMHCE* (g/mi)	CH3OH* (g/mi)	CO (g/mi)	NOx (g/mi)	Aldy. (mg/mi)
Sep 1986	1570	0.13	0.02	0.18	0.37	0.77	0.55	6.6
Dec 1986	1720	0.09	0.01	0.13	0.25	0.74	0.76	11.3
Jul 1987	2055	0.08	0.01	0.10	0.19	0.93	1.11	12.1
Jul 1988	3850	0.07	0.02	0.09	0.16	1.84	0.73	11.0
Oct 1988	4450	0.05	0.01	0.07	0.12	1.00	0.89	9.5
Feb 1989	7550	0.06	0.02	0.08	0.14	1.22	1.01	10.2
Mar 1989	10800	0.06	0.02	0.08	0.12	0.92	1.42	12.3

* Per rulemaking as originally proposed.

FIGURE 1
TOYOTA LCS-M CARINA
EMISSION RESULTS, FTP CYCLE

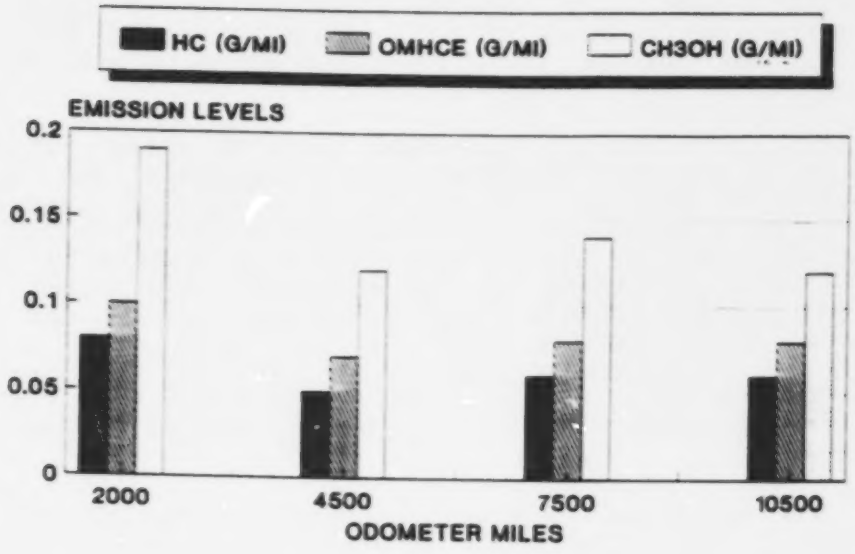
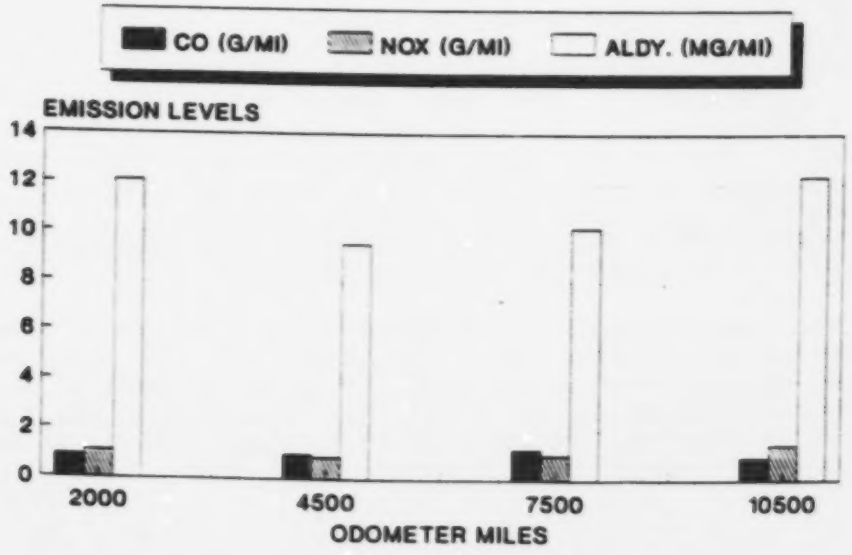


FIGURE 2
TOYOTA LCS-M CARINA
EMISSION RESULTS, FTP CYCLE



Emissions of CH_3OH and OMHCE also did not vary during the mileage accumulation work. Methanol was measured directly during the February and March 1989 testing; prior to this, methanol emissions were computed with an assumed FID response factor of 0.75 and an assumed HC ppm to methanol ppm factor XX/.85, where XX is the fraction of methanol in a methanol/gasoline blend. It may be interesting to note that the calculated CH_3OH level of 0.12 grams per mile during October 1988 is the same as the 0.12 grams per mile measured directly during March 1989.

FTP CO emissions increased to 0.92 grams per mile from 0.77 grams per mile measured during September 1986; however, CO emissions as high as 1.84 grams per mile were measured during July 1988. The CO emissions immediately prior to beginning the durability testing and at the 6,000-mile completion point were essentially unchanged at approximately 1.0 grams per mile. These emissions rose to 1.22 grams per mile at the 3,000-mile point, before falling back to 0.92 grams per mile at the conclusion of the project; the car did not exhibit any driveability problems at 3,000 or 6,000 miles. We are not aware of any reason for this seemingly temporary increase in CO emissions.

NOx emissions have risen since the vehicle was delivered to EPA in 1986. The tests in July 1988 were conducted shortly after the fuel injectors were replaced and a new, slightly richer air/fuel control strategy was utilized; NOx levels fell at that time to 0.73 grams per mile, below the current light-duty vehicle standard. Since then, however, they have crept steadily upward. At the beginning of the durability project, NOx was measured at 0.89 grams per mile over the FTP; NOx levels rose to 1.42 per mile following the completion of the project.

The vehicle as configured during this project was emission tested several times over the FTP during May 1989. While other emission levels did not change substantially during this recent testing, NOx emissions fell to an average of 1.04 grams per mile, approximately the same level measured during February 1989. No driveability problems were noted during the May 1989 testing. Engine-out NOx emissions have been measured at approximately 1.5 grams per mile with an electronic air/fuel calibration optimized for driveability.[11] A maximum lean limit air/fuel calibration, however, gave engine-out emission levels of 1.01 grams per mile for NOx.[11]

The test vehicle is equipped with a manifold close-coupled catalytic converter. This catalyst, by its location in the exhaust stream, may be subjected to greater thermal stress than a catalyst placed in an underfloor location. The increase in thermal stress may assist catalyst light off, but may reduce the effectiveness of rhodium for NOx reduction through

sintering and rhodium diffusion into the alumina support. Wong and McCabe in an unpublished lecture have attempted to explain higher temperature oxidation deactivation of rhodium-containing alumina-supported catalysts.[17] This deactivation may be occurring with this catalyst system; this would be speculative on our part, however, as catalyst surface temperature data is not available.

Formaldehyde levels have remained substantially unchanged since December 1986 levels. The level of 12.3 milligrams per mile measured at the end of this mileage accumulation project is similar to the level of 11.3 milligrams per mile measured in 1986.

HFET cycle emission results are presented in Table 2 and Figures 3 and 4. Emission levels for September 1986 are not available as the vehicle was not tested over the HFET cycle at that time.

Emissions of HC, OMHCE, CH_3OH and CO over the HFET have not changed from December 1986 levels. Figure 2 presents graphically the change in emission levels for these pollutants from December 1986 (1,720 miles) to March 1989 (10,800 miles). The close-coupled manifold converter appears to be very effective at reducing the level of these emissions.

NOx levels over the HFET appear to increase over time. NOx roughly doubled from 0.45 grams per mile to 0.97 grams per mile by July 1987. This level of emissions was maintained until October 1988, the start of the durability project. At the end of the 6,000-mile accumulation, however, NOx had risen to 1.33 grams per mile. This increase is in the same direction as the increase experienced during the FTP testing. Additional tests over the HFET since the completion of this project have not yet been conducted; the recent decrease in NOx emissions over the FTP mentioned earlier in this report may be relevant for the HFET cycle also.

Aldehyde emissions over the HFET appear to have decreased during the mileage accumulation project. The testing conducted in October 1988, at the start of the project, indicated HCHO emission levels of 4 milligrams per mile, down substantially from 8 milligrams per mile measured several months previous. HCHO emissions were measured at 2.2 milligrams per mile at the 3,000-mile mark (February 1989). HCHO then rose slightly at the end of the mileage accumulation to 3.7 milligrams per mile; this level is still substantially below the 8.0 milligrams per mile measured during July 1988.

B. Fuel Economy Testing

Fuel economy test results are presented in Table 3. City, highway, and composite methanol MPG figures are presented as well as gasoline equivalent composite fuel economy. Figure 5 presents graphically city, highway, and composite methanol fuel economy figures with odometer mileage.

Table 2

Toyota LCS-M Carina
Emission Test Results, HFET Test Cycle

Date	Approximate Odometer (miles)	HC (g/mi)	HC* (g/mi)	OMHCE* (g/mi)	CH3OH* (g/mi)	CO (g/mi)	NOx (g/mi)	Aldy. (mg/mi)
Dec 1986	1720	0.007	0.001	0.010	0.019	0.02	0.45	5.7
Jul 1987	2055	0.005	0.001	0.011	0.013	0.04	0.88	10.8
Jul 1988	3850	0.010	0.001	0.010	0.013	0.13	0.83	8.0
Oct 1988	4450	0.002	0.000	0.005	0.007	0.12	0.74	4.1
Feb 1989	7550	0.003	0.000	0.005	0.008	0.05	0.92	2.2
Mar 1989	10800	0.005	0.001	0.008	0.014	0.03	1.33	3.7

* Per rulemaking as originally proposed.

FIGURE 3
TOYOTA LCS-M CARINA
EMISSION RESULTS, HFET CYCLE

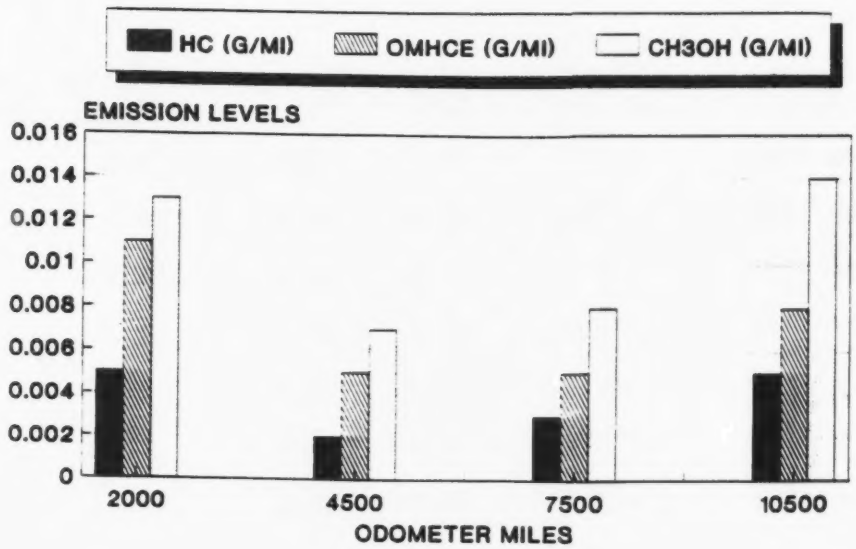


FIGURE 4
TOYOTA LCS-M CARINA
EMISSION RESULTS, HFET CYCLE

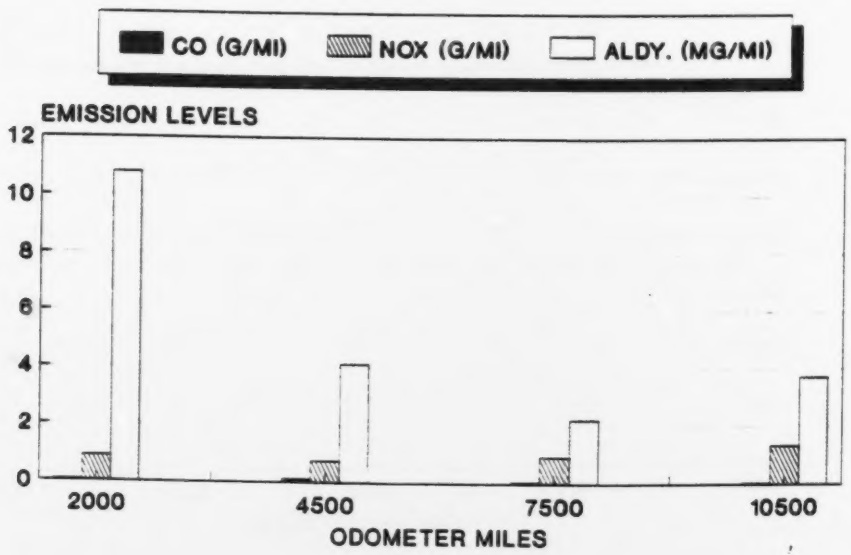


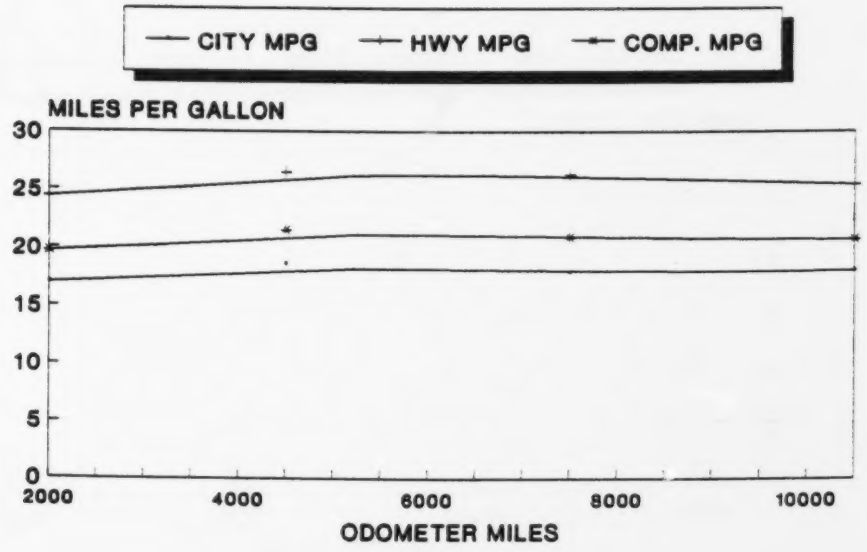
Table 3

Toyota LCS-M Carina

Fuel Economy Test Results

Date	Approximate Odometer (miles)	City MPG	Highway MPG	Composite MPG	Gasoline Equivalent Composite MPG
Sep 1986	1570	18.7	N/A	N/A	N/A
Dec 1986	1720	17.9	25.7	20.7	41.6
Jul 1987	2055	17.0	24.4	19.7	39.6
Jul 1988	3850	18.2	23.7	20.3	40.8
Oct 1988	4450	18.6	26.5	21.5	43.2
Feb 1989	7550	17.9	26.3	20.9	42.0
Mar 1989	10800	18.0	25.4	20.7	41.6

FIGURE 5
TOYOTA LCS-M CARINA
METHANOL FUEL ECONOMY



The gasoline equivalent fuel economy values are based on adjusting for the energy content difference between gasoline and methanol. The nominal energy content of gasoline has been established at 18,507 BTU/lb [18] yielding 114,132 BTU/gallon. Methanol at 8,600 BTU/lb is 56,768 BTU/gallon. The adjustment for M100 fuel based on fuel energy is:

$$\text{Gasoline equivalent adjustment} = \frac{\text{Energy of gasoline}}{\text{Energy of methanol}}$$

Dividing the energy of gasoline:

Gasoline equivalent adjustment = 2.0105

FTP fuel economy was essentially unchanged by this project. Methanol MPG was computed to be 18.0 miles per gallon at project completion; this figure is very similar to the 17.9 miles per gallon measured during December 1986. At the beginning of the project (October 1988), city MPG was 18.6 miles per gallon; this fuel economy was slightly higher than both preceding and subsequent measurements, however. The change in fuel economy measured over the FTP appears to be negligible when considered over the time period from when the test vehicle was first loaned to EPA to the end of the mileage accumulation project.

Fuel economy over the highway cycle has been relatively steady over time; the 25.7 miles per gallon measured at 10,800 odometer miles is the same level as the 25.7 miles per gallon measured during December 1986.

C. Lubricant Analysis

Published reports have indicated that the use of methanol fuel may result in engine wear rates that exceed those of comparably sized gasoline-fueled engines.[19,20] Typically, this increased wear is described as having occurred in the top piston ring and upper cylinder bore area.[21]

Toyota specified an oil change interval of 3,000 miles when the Carina was delivered to EPA for evaluation. We requested that the contractor change the oil and filter at a more conservative 1,500-mile interval during this project. The used oil was then returned to EPA for metals analysis. Samples of the oil were sent to the FRAM, Inc. laboratory in Indianapolis, IN for analysis under the FRAM CODE program.

Table 4 specifies the number of miles accumulated between oil changes and the viscosity characteristics of the lubricants used. The oil had been changed shortly prior to the vehicles initial consignment to ATL; a 30-weight oil specially formulated for use in methanol engines was added at that time. As the number of miles driven with this oil was less than 500 at the start of the durability experiment, the vehicle was consigned with this oil still in the engine. This oil was sampled after roughly 1,500 miles had been accumulated in the Durability project, and the sample is referred to as sample 1.

A multi-viscosity oil, also specially formulated for use in methanol engines, was provided to ATL for replacement of the oil at the specified change intervals. Samples of the used oil are designated as samples 2, 3, and 4 in Table 4. It was thought that this oil change scheme would allow us to evaluate both oils under more controlled driving conditions.

Results from testing individual oil samples from this project are presented in Table 5. Four wear metals are selected for discussion here: iron, aluminum, chromium and copper. These four are of particular interest because they relate to major engine components.[22]

Sample 1, the 30-weight oil in the engine at the start of the program, showed considerably greater metals wear than the multi-viscosity oil samples. FRAM flagged the iron (Fe), aluminum (Al), and chromium (Cr) levels from the first sample as being of particular concern; their standards indicated that these levels suggested that high engine wear was occurring. Sample 1 copper (Cu) levels were not unusually high, according to FRAM.

There may be several reasons for the higher wear metals observed in sample 1. First, the sample 1 oil was run in the engine approximately 500 miles longer than the oil in samples 2, 3, and 4; longer periods of engine operation with the same oil may cause higher levels of wear metals to accumulate. (The 500 miles of driving prior to the initial consignment of the vehicle to ATL was done on a chassis dynamometer over the FTP and HFET cycles at 72°F; the vehicle was not cold started below 72°F during this time.) Second, the flow characteristics of the two oils are quite different; the multi-viscosity oil may have provided better lubricity during cold start, even at 70°F. Finally, the additive packages in the oils were substantially different. The oils were formulated by two different companies; information concerning additive packages, viscosity range testing, etc., is proprietary to the manufacturers.

FRAM stated that the levels of Fe and Al in sample 2 were of moderate concern as wear indicators given our oil change history. Samples 3 and 4 exhibited Fe and Al levels not high enough to comment upon, given their wear criteria. Cr levels were flagged for concern in all samples. The level of Cr in samples 2, 3 and 4 was described as of moderate concern only. FRAM indicated that Cr levels should be monitored in the future, but also suggested that no corrective action need be taken at the present time. Cu levels were not high enough to warrant flagging according to FRAM standards.

Pefley in SAE Paper 831704 [22] provides oil analysis wear metals data from a small fleet of methanol-fueled sedans. These vehicles were powered by a 1.6-liter VW engines; vehicle weight and engine displacement were similar to the Toyota

Table 4

Toyota LCS-M Carina, M100 Fuel
Oil Change Intervals

Sample Number	Odometer Oil Change (miles)	Mileage Between Changes (miles)	Type Of Oil Used
	3907		
1	5900	1993	30 Weight
2	7540	1640	Multi-viscosity
3	9104	1564	Multi-viscosity
4	10748	1644	Multi-viscosity

Table 5

Toyota LCS-M Carina Durability Project
Metal Contaminants In Individual Samples

Metal Contaminant	Sample 1 (ppm)	Sample 2 (ppm)	Sample 3 (ppm)	Sample 4 (ppm)
Fe	143	61	43	43
Al	40	19	14	13
Cr	53	36	26	29
Cu	28	7	4	3

Carina test vehicle used in this project. The oil used in Pefley's work was a commercially available SAE 20W-40 SF-CC oil. The oil was sampled every 1,000 miles and was changed at 3,000-mile intervals. Pefley's vehicles were driven from 7 to 17,000 miles; oil sampling did not occur during the first 3,000 miles of break-in driving. Numerical averages of Pefley's wear metals data are presented in Figures 6 through 9 together with sample 1 and average sample 2-4 data from the Carina durability project for rough comparison. Data from a gasoline-fueled control vehicle from SAE Paper 831704 is also included for comparison. It must be remembered, however, that the engines and vehicles from the durability project and those used in SAE Paper 831704 are different.

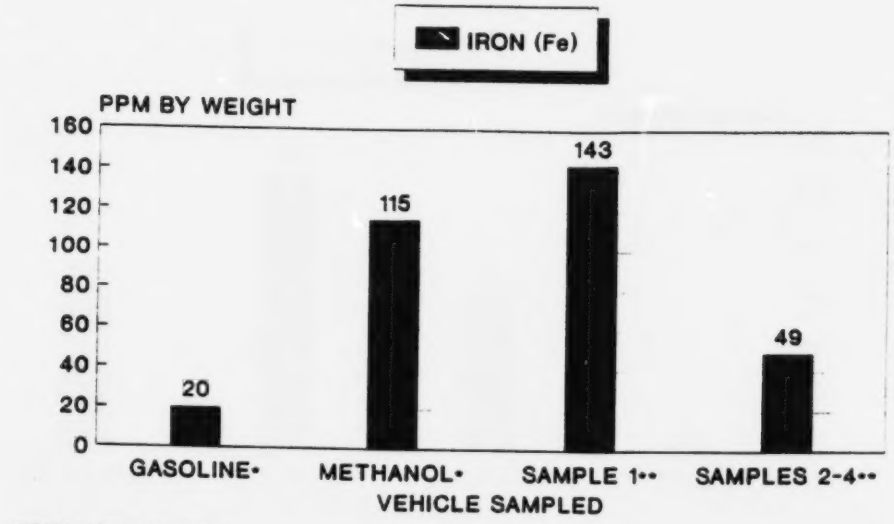
The Fe level of 143 ppm from sample 1 is high even compared to the methanol-fueled vehicle sample average of SAE Paper 831704. The average Fe levels from samples 2-4 were less than half of the 115 ppm methanol vehicle level from SAE 831704. The Fe content of the oil from samples 2-4 is roughly twice as high as the content of the gasoline-fueled control vehicle from SAE Paper 831704, however.

Aluminum levels measured in samples 2-4 from the current project were roughly one-third the level measured with the single-weight oil from sample 1. As in the case of Fe, the extent of metal contamination with the multi-weight oil used in this study was much less than the 68 ppm aluminum measured in the methanol-vehicle oil samples from SAE Paper 831704. Aluminum in the gasoline-fueled vehicle oil was still less than the 15 ppm average aluminum level from samples 2-4.

Average chromium levels in methanol-fueled engine oil samples from both the durability project and the methanol engine test fleet from SAE Paper 831704 appear to be substantially higher than the average from the gasoline-fueled control vehicle. Higher levels of chromium may be related to a larger amount of chromium found in engine parts designed for use in methanol-fueled engines.[23,24] Different materials used in common engine parts would make more difficult even an indirect comparison such as attempted here. It is interesting to note, even without the information suggested above as necessary, that approximately the same degree of Cr contamination was present in the multi-weight oils used in samples 2-4 and methanol-fueled engine in SAE Paper 831704.

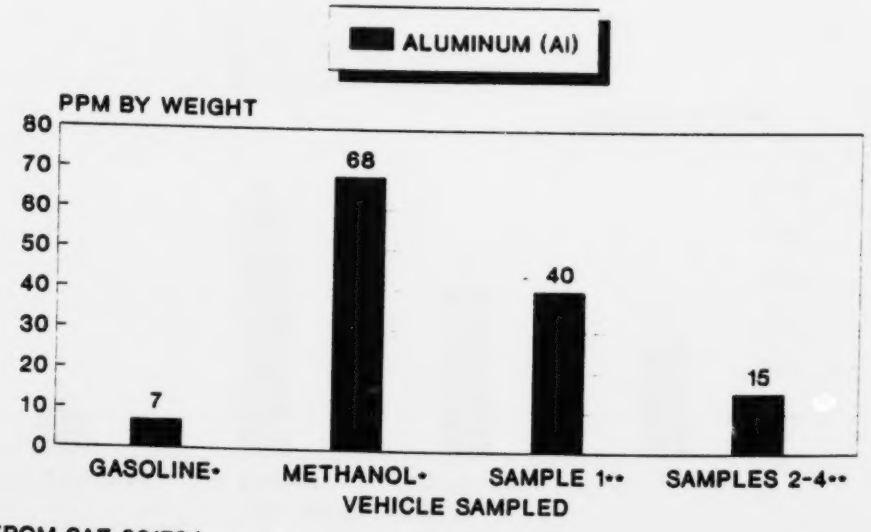
Cu contamination in samples 2-4 was significantly below the 13 ppm Cu measured in the gasoline-fueled engine from SAE Paper 831704. Cu measured in methanol-fueled engine oil from SAE Paper 831704 was roughly four times the level of the 5 ppm measured in samples 2-4.

FIGURE 6
OIL ANALYSIS - METAL CONTAMINATION
COMPARISON WITH PUBLISHED DATA



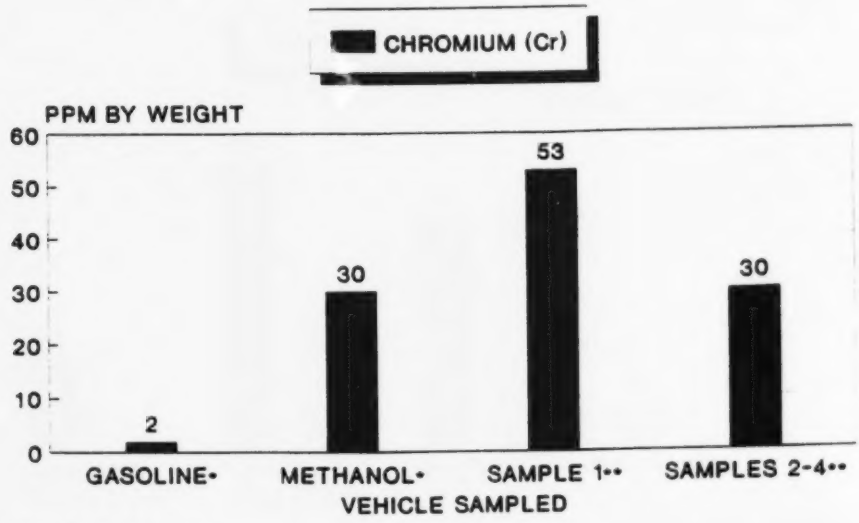
*FROM SAE 831704
**DURABILITY EXPERIMENT

FIGURE 7
OIL ANALYSIS - METAL CONTAMINATION
COMPARISON WITH PUBLISHED DATA



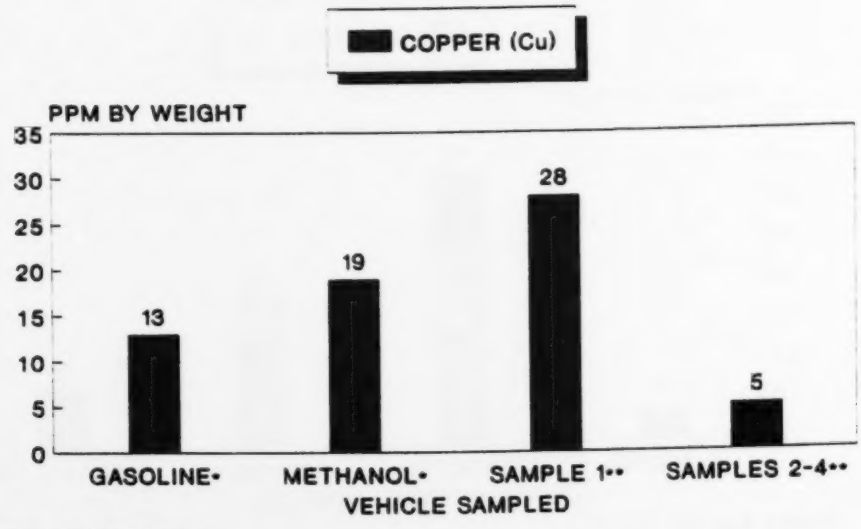
*FROM SAE 831704
**DURABILITY EXPERIMENT

FIGURE 8
OIL ANALYSIS - METAL CONTAMINATION
COMPARISON WITH PUBLISHED DATA



•FROM SAE 831704
••DURABILITY EXPERIMENT

FIGURE 9
OIL ANALYSIS - METAL CONTAMINATION
COMPARISON WITH PUBLISHED DATA



•FROM SAE 831704
••DURABILITY EXPERIMENT

VII. Test Highlights

1. Emissions of HC, OMHCE, CH_3OH, CO and HCHO over the FTP cycle did not substantially change over the 6,000 miles of durability testing. Emission levels of these pollutants at the completion of the durability project were similar to emission levels during July 1989, several months prior to the start of this work.

2. NOx levels over both the FTP and HFET cycles increased substantially during the project. This increase in NOx emissions may be related to oxidative deactivation of the rhodium catalyst.

3. City and highway fuel economy was essentially unchanged by this project; the gasoline-equivalent composite MPG measured during March 1989 was the same as that measured during December 1986.

4. The oil sample taken after the first 1,500 miles of driving during the project showed metal contaminant levels twice as high as samples taken during the remainder of the mileage accumulation. The oil from this first sample was 30-weight oil; approximately 500 chassis dynamometer miles had been accumulated with this oil in the engine before durability testing commenced. The oil was then changed to a multi-viscosity oil; this multi-weight oil was used during the remainder of this project. The multi-weight oil may have improved the level of metal wear over that of the single-weight oil. Differences in driving cycles could have contributed to this difference in wear level between the two oil types. Each multi-weight oil sample was taken after approximately 1,550-1,650 miles of driving over the AMA durability cycle.

VIII. Acknowledgments

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APPENDIX A

DESCRIPTION OF TOYOTA LCS-M TEST VEHICLE

The Durability Driving Schedule for light-duty vehicles consists of eleven laps of a 3.7-mile course. The basic vehicle speed for each lap is given below.

Table A-1

Basic Lap Speed
Durability Driving Schedule

Lap	Speed (miles per hour)
1	40
2	30
3	40
4	40
5	35
6	30
7	35
8	45
9	35
10	55
11	70

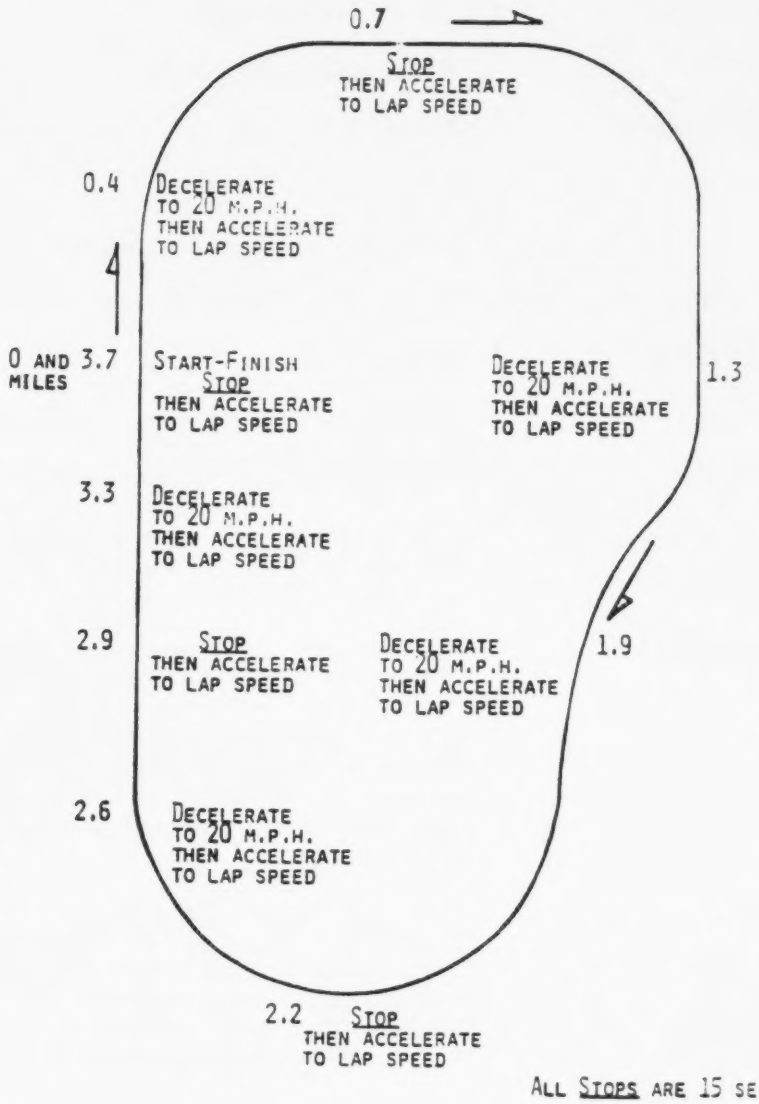
Each of the first nine laps contain four steps with 15-second idle periods. These laps also contain five light decelerations from base speed to 20 miles per hour followed by light accelerations to the base speed. The tenth lap is run at a constant speed of 55 miles per hour. The eleventh lap is begun with wide-open throttle acceleration from stop to 70 miles per hour. A normal deceleration to idle followed by a second wide-open throttle acceleration occurs at the midpoint of the lap.

Figure A-1 below is a diagram of one lap of the Durability Driving Schedule taken from 40 CFR, Chapter 1, Part 86, Appendix IV.

Figure A-1

Durability Driving Schedule Lap

(From 40 CFR, Chapter 1, Part 86, Appendix IV)



ALL Stops ARE 15 SECONDS

APPENDIX B

DESCRIPTION OF TOYOTA LCS-M TEST VEHICLE

Vehicle weight	2015 lbs
Test weight	2250 lbs
Transmission	Manual, 5 speed
Shift speed code	15-25-40-45 mph
Fuel	M100 neat methanol
Number of cylinders	Four, in-line
Displacement	97 cubic inches
Camshaft	Single, overhead camshaft
Compression ratio	11.5, flat-head pistons
Combustion chamber	Wedge shape
Fuel Metering	Electronic port fuel injection
Bore and Stroke	3.19 inches x, 3.03 inches
Ignition	Spark ignition; spark plugs are ND W27ESR-U, gapped at .8 mm, torqued to 13 ft-lb.
Ignition timing	With check connecter shorted, ignition timing should be set to 10°BTDC at idle. With check connecter unshorted, ignition timing advance should be set to 15°BTDC at idle. Idle speed is approximately 550-700 rpm.
Fuel injectors	Main and cold start fuel injectors capable of high fuel flow rates. The fuel injector bodies have been nickel-plated, and the adjusting pipes are stainless steel.

APPENDIX B (CONT'D)

DESCRIPTION OF TOYOTA LCS-M TEST VEHICLE

Fuel pump	In-tank electric fuel pump with brushless motor to prevent corrosion. The body is nickel plated and its fuel delivery flow rate capacity has been increased.
Fuel tank	Stainless steel construction; capacity 14.5 gals.
Fuel lines and filter	The tube running from the fuel tank to the fuel filter has been nickel plated. The fuel filter, located in the engine compartment, has also been nickel plated. The fuel delivery rail has been plated with nickel-phosphorus.
Catalytic converter	1-liter volume, Pt:Rh loaded, close coupled to the exhaust manifold.